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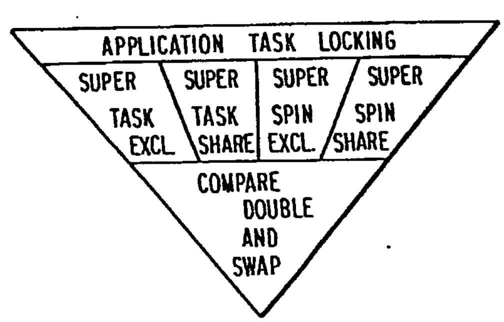
(71) Applicant: International Business Machines Corporation, Old Orchard Road, Armonk, N.Y. 10504 (US)

(72) Inventor: Hough, Roger Eldred, 7 Sharon Drive, Highland New York 12528 (US)

(74) Representative: Herzog, F. Joachim, Dipl.-Ing., Schönaicher Strasse 220, D-7030 Böblingen (DE)

(54) **Non-spinning task locking using compare and swap.**

(57) A method for controlling both shared and exclusive access for a resource in a multiprocessor system wherein a first-in/first-out queue is formed for tasks suspended while awaiting access and wherein access to the resource provides that control of access required for manipulation of the first-in/first-out queue which is not provided by the atomic nature of compare (double) and swap. Each member of the queue has indicators of the access which it requested and of the next most recently enqueued member which has a corresponding indicator. A lockword is established having two parts, a lock flag indicating the status of the resource, whether available, under shared ownership or under exclusive ownership and a lock pointer pointing to the most recently enqueued task. In requesting or releasing access, an initial guess is made as to the value of the lockword and a projected lockword is calculated based on the guess. Then an atomic reference is made to the lockword during which no other multiprocessor has access to the lockword. During the atomic reference, the lockword is compared to the guess of the lockword and if the guess is correct, the lockword is replaced by the projected lockword which rearranges the queue for the requesting or releasing task. If the guess was incorrect, the value of the lockword is used to calculate another projected lockword. If another task can effect the next tasks to gain access, the process with the atomic reference is repeated until no intervening changes occur between atomic references.



EP 0 145 889 A2

NON-SPINNING TASK LOCKING USING COMPARE AND SWAP

The invention relates generally to the use of lock-words for establishing control and queuing in a multi-task computer environment and, in particular, relates to task locking that avoids spin locking.

In a computer system involving only a single processor executing a single task at any time, the control of computer resources presents no problem. The type of resources being referred to can be mass memories, tape drives, printers or communication channels, although other types of resources are understood to exist. Only one task exists to have access to any resource and maintains its control over all the any resource as well as the central processing unit until the requested resource has completed its activity.

However, multi-tasking and multiprocessor systems have become popular which allow simultaneous or interleaved execution of multiple tasks with the resources somehow shared between the simultaneously executing tasks. Some resources like a printer or a tape drive operate such that the requesting task requires exclusive access to that resource for at least some period. Other resources, such as parts of a common storage area, may be shared among various tasks. In order to arrange controlled access to a resource, a queue is set up for all tasks that have requested access to a resource but are not granted immediate access. The queue must further contain the information as to whether a task in the queue is requesting shared or exclusive access of the resource and whether the resource is currently being used on a shared or exclusive basis.

Thus, when a task requests access to a resource but is refused immediate access, the operating system rearranges the queue to reflect the addition of the requesting task to the queue. However in a multi-tasking environment, the possibility always exists that two or more tasks will request access to a particular resource at almost the same time and, if not prevented, will proceed to rearrange the queue concurrently. This rearrangement largely involves serializing the queue, that is, setting up an ordered list of who is in the queue. If this rearrangement is being performed concurrently by two different tasks, one of the requesting tasks may not join the queue or, even worse, the entire organization of the queue will be destroyed.

In order to avoid these problems, a lockword is established for each resource. If the queue for that resource is currently being rearranged, the lockword indicates this fact, and the operating system prevents a second task from manipulating the queue. However, if the lockword indicates that no queue manipulations are in progress, then the requesting task first changes the lockword to assert ownership of queue manipulations for that resource and proceeds to rearrange the queue according to its requirements.

At the end of the queue manipulation, the lockword is reset to a state indicating that no queue manipulation is currently in progress.

To avoid all possibility of two tasks concurrently rearranging the queue, the initial testing and setting of the lockword must be performed such that only a

single task can at any time be performing this pair of operations.

In an IBM System/370, designed for a multi-tasking environment, there is a test and set instruction which can fetch a word from memory, test for a specific bit and return a modified word to the memory, all during one operation in which all other tasks or processors are barred from accessing that particular word in memory. The fetch and return-store forms an atomic unit or atomic reference which, once begun, cannot be interrupted by or interleaved with any other CPU in a multi-processor. The test and set instruction can therefore be used to test a lockword and to set it for ownership. The set of operations is described in Table 1 in which one bit of the byte LOCKWORD is tested for zero, indicating availability of the lockword. LOCKWORD is immediately rewritten with this bit set to a "1". The result of this testing is retained and used in the next step by a conditional branch BC. If the testing was not successful, i.e., the lockword was owned by another task or processor, execution branches back to retry, the test and set operation. When the lockword is available and ownership of the lockword is established, a series of operations are performed in which the queue is manipulated by this requesting task or processor. While this manipulation is proceeding, no other task can manipulate the queue because this task owns the lockword. When the manipulation has been completed, a final instruction rewrites the lockword to indicate that it is once more available. LOCKWORD is set to zero, indicating that the queue is once more available to other requesting tasks or processors.

```
retry    TS     LOCKWORD
         BC     CC1,retry
                .
                .
                .
          alter queue
                .
                .
                .
         MVI    LOCKWORD, 0
```

SPIN-LOCK
TABLE 1

The above series of operations is called spin-locking because, if a task cannot gain ownership of a lockword, it keeps spinning or trying to obtain such ownership until the using task finally relinquishes control. Such spinning is wasteful and in some situations can severely degrade the throughput of a multi-tasking computer. A particularly bad situation occurs if one processor is in spinlock because a second processor owns the lockword and then the second processor fails before it relinquishes the lockword. In this case, the first processor continues to spin for an indefinite time because of the failure of another processor.

A pictorial illustration of the hierarchy involved in task locking implemented with test and set is shown in Fig. 1(A). Test-and-set is too primitive to provide direct identification of the owning task or processor for a lockword when a CPU failure occurs or to provide more than one owner of a resource. For this reason, test-and-set is used to control manipulation of small queues, which may consist of single elements, that in

turn control the manipulation and examination of other queues. These elements allow the identification of the task or processor owning the queue when a CPU failure occurs and provide the ability for more than one task to have ownership of a queue at the same time, as might be useful for tasks which examine a queue without altering it.

The enhanced spin locks are, in turn, used to control the manipulation of queues for which tasks, but not processors, are suspended until the required availability. Requests which allow concurrent ownership to others are called "shared" requests. Requests which allow no other concurrent ownership are called "exclusive" requests. Requests which cause the task to be suspended without suspension of a processor are called "task locks".

The first level of task locks provides control for resources and queues on which the operating system is dependent for its continued operation. These are called "supervisor task locks", since they are available only to supervisory programming.

One of the supervisor task locks is used, in turn, to control the manipulation of queues which provide control for resources and queues on which the operating system is not dependent for its continued operation. These are called "application task locks", since they are available to any programming.

The importance of the hierarchy is that application task locking requires four levels of operations. The multiplicity of levels produces a complex and slowly operating system.

An important capability of the System/370 series of processors is made possible by two instructions, named "compare and swap" and "compare double and swap". The two instructions differ only in that compare and swap operates on single length words, while compare double and swap operates on double length words. As used here, a word is four bytes (thirty-two bits) long while double words are twice that length. Because the embodiment to be described later uses double words, only compare double and swap is described.

The compare double and swap or CDS operates on three operands so that it assumes the form of CDS (OLD, NEW, LOCK), where OLD, NEW and LOCK are double length words. The effect of CDS is illustrated in Fig. 2. If the value of LOCK equals or matches the value of OLD, then LOCK is replaced with the value of NEW; however, if LOCK does not match OLD, then OLD is replaced with LOCK and LOCK remains unchanged. A condition code CC is set depending on the outcome of the test for LOCK = OLD. This condition code can be used to separate the operational flow depending on the success of the test.

The CDS operation shares the attribute with test and set that it is an atomic reference. That is, it fetches and stores back into memory in a single operation that cannot be interrupted by any other processor. Although, Fig. 2 shows five operations, CDS is accomplished as though it were a single operation. This atomic character, coupled with its similarity to test and set, allows CDS to replace the test-and-set operation in a supervisor spin exclusive. Indeed means have been described elsewhere to use compare double and swap in both a supervisor spin share and a supervisor task

exclusive. These possible uses of CDS are shown in the hierarchy shown in Fig. 1(B). The result is that for exclusive tasks, only three levels of operations are required for application task locking. Until now, shared access task locking has required the use of a supervisor spin or exclusive task lock to control access to the controls which, in turn, are used to provide shared access and coordinate shared access with exclusive access requests for the same queues or resources.

Because the suspension and resumption of a task cannot itself be suspended and resumed as a task, the lock which controls its queues must necessarily be a spin lock. If this spin lock is not the same lock used to control access to the controls used to provide shared access, another level of locking may be introduced when a task must be suspended or resumed for the lack of availability or the reappearance of availability of a resource. These three levels are an improvement over the four levels required with test and set. However, the three levels still introduce system complexity with shared tasks. Furthermore, they contribute to unwanted system complexity and slow its operation.

Accordingly, the main object advantageously solved by this invention is to provide task locking with a minimum level of operations between the instruction set and the application task locking.

A further object advantageously solved by the invention is to provide shared and exclusive task locking that as much as possible avoids the use of other locks.

The invention can be summarized as a method of providing task locking for any combination of tasks requesting either shared or exclusive access to a resource. A first-in/first-out queue is created by control blocks indicating both the type of access requested and a pointer to the next previously enqueued control block. A lockword controls access to the queue of the resource and indicates both the present use of the resource and a pointer to the most recently enqueued task in the queue. Methods using the atomic operation, compare double and swap, allow a task requesting either exclusive or shared access of the resource to be enqueued and allow tasks releasing either exclusive or shared access to the resource to suitably rearrange the queue and prepare access to the resource for other tasks.

In the following specification the invention is described in detail in connection with examples shown in the drawing in which

Figs. 1(A) and 1(B)	are illustrations of the hierarchy required by prior art application task locking;
Fig. 1(C)	is an illustration of the hierarchy involved in application task locking with the present invention;
Fig. 2	is a flow diagram of the atomic operation compare double and swap;
Fig. 3	is a pictorial representation of a queue for a resource as used in this invention;

Fig. 4 is a flow diagram of the processing of a request for exclusive access to a resource;

Fig. 5 is a flow diagram of the processing of a request for shared access to a resource;

Fig. 6 is a flow diagram of the processing of a release of shared ownership of a resource;

Fig. 7 is a flow diagram of the processing of a release of exclusive ownership of a resource;

Figs. 8(A) and 8(B) are pictorial illustrations of queues useful in understanding Figs. 7 and 9;

Fig. 9 is a flow diagram for the step of identifying the status of the queue of Fig. 7; and

Fig. 10 is a flow diagram for the step of abnormal termination clean-up of Fig 7.

The architecture of the task locking according to this invention will be described with reference to the block diagram of Fig. 3. If one or more tasks has requested access to a resource but their requests cannot be honored, then the request is put into a queue. The first queued request can be rejected because the task currently executing on the resource is a task requiring exclusive access to that resource or the requesting task can itself be requesting exclusive access when

the resource is already owned either exclusively or shared. If the resource is not currently busy, a request is immediately honored and no queue is formed. In the absence of a queue, if one or more tasks currently have shared access to the resource, then an additional request for shared access is immediately honored and there is no reason to form a queue. The queue will have the architecture of a first-in/first-out queue. That is, a request for access to the resource is honored for the oldest or least recently submitted request before a more recent request is honored. This means that if an older request is a request for exclusive access, a more recent request for shared access will be denied, even if the resource is currently being used with shared access. If the resource is currently in use for shared access, then the top of the queue or the least recently enqueued task will necessarily be a request for exclusive access. Previously submitted requests for shared access would have been honored and the associated task removed from the queue. However, requests for shared access, less senior than an enqueued exclusive request, may be in the queue. The queue is formed of a series of task deferral control blocks (TDCB) arranged at arbitrary locations in a memory 22 of the multi-processor system. It should be noted that the resource may also be a part of the memory 22. A separate task deferral control block is set up for each task that has been suspended because a request for access to the resource has been denied. Each task deferral control block contains a variety of information. It must contain all information required to resume the suspended task, such as a pointer to the task or a control program event control block to be posted. It must also contain an indication specifying whether shared or exclusive access SH/EXCL was requested for this task.

Of course this indication can be omitted if only one form of access is permitted. Finally, for the purposes of this invention, it contains a pointer NCB to the next most recently enqueued task deferral control block, if any. The NCB of the top, least recently queued element of the queue is set to zero.

The lockword is a double word (LOCK = LOCKFLAG: LOCKTPTR) and is stored at a fixed position within the memory 22. The lockword controls access to the resource and to the queue for the tasks awaiting access to the resource. The first half LOCKFLAG of the lockword indicates the current usage of the resource. If the resource is not currently in use and no task has access to it, LOCKFLAG = 0. If the resource is currently held shared, LOCKFLAG is the negative of the number of tasks which have shared access to the resource. If the resource is currently held exclusively, LOCKFLAG is a positive number, which may further designate the exclusively owning task. The second word LOCKTPTR of the double word LOCK is a pointer to the task deferral control block of the most recently enqueued task. If there are no enqueued tasks, i.e. no queue, then LOCKTPTR = 0. Thus, LOCKTPTR points to the most recently enqueued task deferral control block.

The queue as described has a dynamic architecture. If the senior member of the queue is given access to the resource, its task deferral control block TDCB-1 may be de-allocated from the memory 22. Then the NCB of the next least recently enqueued task TDCB-2 is set to zero, indicating that TDCB-2 is now at the top of the queue. Also, the first word LOCKFLAG of the lockword is reset to reflect the new status of the resource. If another task is to join the queue, another task

deferral control block is allocated and the second word LOCKTPTR of the lockword is set to point to this newly allocated task deferral control block. The NCB of this new task deferral control block is set to point to the task deferral control block of the next recently enqueued task, TDCB-4 in the example.

According to the invention, any task wishing to rearrange the queue because it is requesting or releasing access to the resource, makes a guess as to what the present lockword is and forms a new potential lockword NEW based on its guessed lockword. In a compare double and swap, the task causes the guessed lockword to be compared with the present lockword LOCK. If the guess was correct, then the present lockword is replaced by the new lockword NEW and the rearrangement has been accomplished. Because of the atomic nature of the compare double and swap, the rearrangement is accomplished while other tasks on other multiprocessors are barred from access for modifying the lockword.

However, if the guess at the present lockword was incorrect, the actual value of LOCK is used to produce a potential NEW lockword. Then the compare double and swap is repeated and, presuming no other task has in the meantime rearranged the queue and modified the lockword LOCK, the subsequent compare double and swap rearranges the queue.

An embodiment of the invention will be described for four different situations when the resource can be used exclusively by one task or can be shared among multiple tasks: a request for exclusive access, a request for shared access, a release of exclusive access and a release of shared access. In this dis-

cussion, the double-word lockword contains two single words, LOCK = LOCKFLAG:LOCKTPTR. Both the double-word and single-word representations will be used depending on the operation. Likewise, the predicted new lockword NEW is a double-word consisting of two single words, NEW = NEWFLAG:NEWTPTR. Similarly, the fetched value of the lockword OLD = OLDFLAG:OLDTPTR. In the flow diagrams, the conditional branch on the condition code CC in Fig. 2 will be implicitly included in the compare double and swap so that the exit from that operation assumes one of two paths, depending on the outcome of the comparison of LOCK with OLD.

The method for processing a request from a task for exclusive access is shown in the flow diagram of Fig. 4. The process starts from point 30. An initial guess is made that the resource is not currently in use so that the value of LOCK is predicted to be (0, 0). This value is stored in the double-word OLD. If this is true, then the requesting task can gain immediate access to the resource, in which case LOCKFLAG would be set to designate this requesting task as exclusive owner and LOCKTPTR would be set to zero indicating that no other tasks are enqueued. If in fact a queue presently exists, the resource must necessarily be in use. These new values for the lockword are set respectively into NEWFLAG and NETPTR. Then the atomic reference compare double and swap 31 is executed. The lockword LOCK is fetched and compared with the double-word OLD. If the two values match, then the prediction is correct and LOCK is replaced with the value of NEW and exclusive access has been gained to the resource. In this case, no queue previously existed and no queue needs to be created because the requesting task has not been deferred.

However, if OLD does not match LOCK, then the prediction of an available resource is untrue. Then the current value of the lockword is stored in OLD. It is to be once more emphasized that compare double and swap is an atomic reference so that if the prediction was true at the beginning of the execution of CDS, then access was gained to the resource without another multiprocessor being able to change the situation in the middle of the operation. Likewise, the value of LOCK that is stored in OLD is the value at the beginning of the execution of CDS.

If the resource is not now available for exclusive access, execution of the request reaches point 32 and preparations are made for putting the current or requesting task into a queue. A task deferral control block is prepared and the contents of this block are set up for the current task along with an indication that it is a request for exclusive access. Preparations are made to put the current task into the queue, which previously may not have existed. At this point 34, the best current prediction for the value of the lockword is the value OLD obtained in the compare double and swap 31. The value of LOCKFLAG would not change if the current task is put in the queue so NEWFLAG is replaced by OLDFLAG. However, the updated LOCKTPTR would point to the current task which upon enqueuing would be the most recently enqueued task. The NCB of the task deferral control block for the current task would point to the task deferral control block pointed to by the previous LOCKTPTR, at that time the most recently enqueued task. Accordingly, the value of NEWTPTR is replaced with the identification, normally the address, of the task deferral control block of the current requesting task and the next block pointer NCB in the current task

deferral control block is replaced with the value of OLDTPTR. Then another atomic reference 36 in a compare double and swap is performed. If the lockword remains as it previously was so that OLD = LOCK, then LOCK is replaced with NEW and the current task is placed in the queue with the pointers corrected for the correspondingly rearranged queue. The execution of the current task is suspended as it awaits access to the resource and the task is enqueued. If, however, since the last compare double and swap 31, some other task has rearranged the queue by modifying the lockword, then OLD does not match LOCK and the current value of LOCK is placed into OLD.

At this point 38, a decision is made as to whether the change in state is due to the resource becoming available or whether the resource is again unavailable but the queue has been rearranged. If OLD = (0, 0), then the best guess is that the resource is now available so that it is no longer necessary to form a queue. The space for the task deferral control block for the current task is de-allocated if necessary, and execution returns to the start 30. However, if OLD ≠ (0, 0), then a change has been made to the queue but the resource is not available. Execution then returns to point 34 with the value of OLD having been obtained from the compare double and swap of the recent atomic reference 36 rather than first atomic reference 31.

The execution of a request for shared access, as illustrated by the flow diagram of Fig. 5, proceeds similarly to that for a request for exclusive access, except the case needs to be included in which the resource is currently under shared access but there is no queue currently existing so that the requesting task can gain

shared access to the resource. As previously stated for a first-in/first-out queue, a shared access request cannot jump ahead of an exclusive access request in the queue. Also, it is assumed that the resource can accommodate all requests for shared access if it is already under shared ownership so that the existence of a queue when the resource is shared implies that the top, most senior least recently queued task in the queue is requesting exclusive access.

The execution for a request for shared access starts at point 40 with an initial prediction that the resource is not only available but that no other tasks currently are sharing access of that resource. The predicted value of LOCK, i.e., (0, 0), is placed into OLD. If this prediction is true, then upon successful storing by compare double and swap shared access will have been established for this single task, LOCKFLAG will equal -1, indicating that there is only one task, the current task, in shared access of the resource. Furthermore, LOCKTPTR will be 0 because there will be no task deferral control blocks to point to. These two values are placed into NEW. At this point 42, an atomic reference 44 is performed with a compare double and swap. The lockword LOCK is fetched and compared with OLD and if the two double words match, the prediction is true and LOCK is replaced by the predicted new lockword NEW so that the request for shared access can immediately be honored. A shared ownership flag is set indicating shared ownership of the resource by the current task to allow abnormal termination recovery. Thereupon shared access is attained. However, if the prediction was not true so that OLD does not match LOCK, the value of the lockword is placed into OLD.

At this point 46, the failure of the prediction can be caused either by the existence of a queue which implies there is a more senior task requesting exclusive access already in the queue or there is no queue but one or more tasks already have access to the resource. If OLDFLAG $\leqslant$ 0 and OLDTPTR = 0, then there is no queue but the resource is already shared. The test for OLDFLAG being zero needs to be included at this point because the paths passing through this decision point 46 can originate from points other than the start 40. If the test is true so that there is no queue and no exclusive ownership of the resource, the best guess for an updated value of LOCKFLAG would be its old value decremented by 1, indicating that one more task, i.e., the current task, has gained shared access to the resource. Therefore, NEWFLAG is replaced by OLDFLAG - 1 and execution returns to point 42 for re-execution of the compare double and swap 44.

However, if OLDFLAG > 0 or OLDTPTR $\neq$ 0, then the current task will need to be queued. A task deferral control block is prepared with an indication that shared access is requested for the current task. At this point 48, preparations are made to rearrange the queue based on the previously fetched lockword. NEWFLAG is replaced with the value of OLDFLAG. NEWTPTR points to the task deferral block of the current task by being replaced with its identification. The current task deferral control block points to the next most recently enqueued task deferral control block by the replacement of its NCB with OLDTPTR.

Then a new atomic reference 50 is made using compare double and swap. If the lockword has not changed since the last atomic reference, OLD matches LOCK and the

lockword is updated by the predicted new lockword by replacing LOCK with NEW so that the current task is properly enqueued. The current task is then suspended awaiting availability of the resource for which it has been enqueued.

However, if the lockword fetched in the atomic reference 50 has been changed since the last atomic reference, OLD does not match LOCK and OLD is replaced by the current lockword LOCK. This failed test may be due to the queue's disappearing since the last atomic reference and the resource being available or under shared ownership. In this case, which is tested by the conditions OLDFLAG $\leqslant$ 0 and OLDTPTR = 0, it means that the current task can probably gain immediate shared access to the resource. Therefore, the task deferral control block is disposed of and the current LOCKFLAG is prospectively decremented by replacing NEWFLAG by OLDFLAG - 1. Execution then returns to point 42 for re-execution of the atomic reference 44 using compare double and swap.

However, if the lockword has been modified but a queue still exists, or the resource is held in exclusive access, as indicated by OLDTPTR being loaded with a non-zero value or OLDFLAG being loaded with a positive value, respectively, an attempt to enqueue the current task is tried by returning execution to point 48. Just as was the situation for a request for exclusive access, a task will be properly enqueued if no other task has modified the lockword between consecutive executions of the atomic references 44 or 50.

When a task having access, either shared or exclusive, to a resource is ready to release its access to that

resource, more is involved in the release of access than simply departing. The queue is maintained in proper form by assuring that upon each release of access, the lockword is properly updated and any task currently in the queue which should now gain access to the resource is taken out of the queue and given appropriate access. A further function is performed upon release and that is to deal with tasks which have abnormally terminated since their task deferral control blocks entered the queue.

The procedure for releasing shared access is illustrated in the flow diagram of Fig. 6. It should be kept in mind that when the resource is under shared ownership, if a queue exists, the top member of that queue is a request for exclusive access. Any more senior request for shared access would have been already honored. The execution of a release of shared access begins at the start 60 where an initial guess is made that no task is enqueued. This would be indicated by LOCKTPTR = 0. It is further assumed that the task releasing shared access is the only task currently using the resource, as indicated by OLDFLAG = -1. If this prediction is true and the current task releases shared access, then the new lockword would indicate no use of the resource and no queue. Accordingly, both single words of NEW are set to 0. At this point 62, an atomic reference 64 is made by a compare double and swap. If the prediction is true so that OLD matches LOCK, then the lockword LOCK is replaced by NEW and the task seeking to release access has succeeded. The flag indicating shared ownership of the resource is cleared because this task is no longer sharing ownership of that resource. Thereafter the task is released and no

further action needs to be performed because no tasks are enqueued.

If, however, the initial prediction was incorrect, then the test will be unsuccessful and the current value of the lockword is placed into OLD. At this point 66, a decision is made as to whether the prediction was wrong because there were other tasks sharing the resource or no queue existed by the conditions, OLDFLAG < -1 and OLTPTR = 0, respectively. The inclusion of the test for OLDTPTR is necessary because this decision point 66 may be reached from other directions than the start 60. If other shared access is to remain or if no tasks are enqueued, then preparations are made for the task to release shared access by prospectively incrementing the negative LOCKFLAG, that is, NEWFLAG is replaced by OLDFLAG + 1 and execution returns to point 62. The execution of the atomic reference 64 will be successful if since its last execution no other task has gained or released shared access to or been enqueued for access to the resource. In the case where, in the interim, the releasing task has been left as the only task sharing access, the test for OLDTPTR = 0 will again return execution to point 62. If, however, no interim changes have been made to either the access or the existence of a queue, the second execution of compare double and swap 64 releases the task from shared access with the resource still being shared by at least one task.

In the remaining case, the task seeking to release shared access is the last task having shared access to the resource and further tasks (the top, most senior, least recently queued one being an exclusive request) are enqueued. Thus execution reaches point 68 and a decision is made as to whether only one task is pre-

sently enqueued, which would necessarily be a request for exclusive access. This decision is made by testing whether the next control block pointer NCB of the task deferral control statement pointed to by OLDTPTR is 0. If the test is successful, that is, OLDTPTR is 0, execution reaches point 70 and preparations are made to eliminate the queue by setting NEWFLAG to the identification of the task for the task deferral control block pointed to by OLDTPTR. As a result, the task for the task deferral control block at top of the queue will have exclusive access to the resource, and a value of NEWTPTR = 0 indicates that no queue will exist on successful completion of the initial store by compare double and swap. Then an atomic reference 72 by a compare double and swap is performed. If the test is successful, LOCK is replaced by the value of NEW and execution proceeds to point 74 where the flag is cleared for shared ownership by the releasing task. The task deferral control block of the senior task in the queue is then disposed of. The senior task is removed from suspension or, if the senior task has abnormally terminated, a release of exclusive access to the resource is issued on its behalf. At this point, the processing for a release of shared access is completed.

If, however, the comparison in the atomic reference 72 was unsuccessful, then OLD is replaced by LOCK. The lack of success can only be caused by an additional task joining the queue since the prior atomic reference 64 so that now at least two tasks are queued. At this point 76, the queue is searched for its most senior member by proceeding from the bottom of the queue to the top by way of the next control block pointers NCB until finally one is found for which NCB = 0. The senior member of the queue is removed from the task by

setting the NCB of the next most senior task deferral control block in the queue to 0. Then by an MP-consistent operation LOCKFLAG is replaced by the identification of the senior task in the queue. An MP-consistent operation is an atomic unit such that its partial execution cannot be seen by another MP-consistent operation, of which compare and swap is one example. With the change of LOCKFLAG, the senior member of the queue has been given access to the resource and execution continues from point 74 for clearing the flag, disposing of the task deferral control block, and removing the senior task from suspension.

If the initial test at point 68 for the queue consisting of a single task failed, execution proceeds to point 76 where the search is initiated for the senior queued task in the subsequent previously described operations.

A release of exclusive access has the simplification that it is known that the releasing task is the only task currently owning the resource. However this simplification is more than compensated for by a lack of knowledge of the status of the top of the queue. The least recently enqueued task may be an exclusive request, as represented schematically by the queue of Fig. 8(A), in which case upon rearrangement the top member of the queue will gain exclusive access to the resource. Alternatively the top of the queue may be occupied by one or more requests for shared access, as shown by the queue of Fig. 8(B). If this is the case, all tasks senior to the top, least recently enqueued request for exclusive access will simultaneously be granted shared access to the resource.

The execution of a release of exclusive access is illustrated in the flow diagram of Fig. 7 and begins from the start 80. Because the resource is held exclusively, the value of OLDFLAG is necessarily the identification of the task attempting to release access. An initial guess is made that there are no tasks enqueued so that OLDTPTR is set to 0 in hope of matching LOCTPTR. The corresponding value for NEW is (0, 0). An atomic reference 82 is made by a compare double and swap. If the guess was correct and OLD = LOCK, then the value of LOCK is replaced by NEW so that the lockword is replaced and exclusive access is successfully released. However, if the match was not true, then OLD is replaced by the value of LOCK because a queue of some sort existed.

At this point 84, the details of the queue must be found. Parameters describing the queue are explained with reference to Figs. 8A) and 8(B). A group of tasks will be granted access to the resource. If the least recently enqueued task is an exclusive task, then BEGPTR will point to the task deferral control block of that senior and exclusive task. BAKPTR will point to the task deferral control block of the next most senior, next least recently enqueued task, if any. If however, as illustrated in Fig. 8(B), one or more requests for shared access occupy the top of the queue, then BEGPTR points to the task deferral control block for the most recently enqueued of the requests for shared access at the top of the queue and BAKPTR points to the task deferral control block of the next most recently enqueued request, necessarily a request for exclusive access if a request exists. In both of these cases, if there are no other tasks in the queue, then BAKPTR = 0. This information can be obtained in block

86 by the series of steps shown in the flow diagram of Fig. 9. The task deferral control blocks in the queue are interrogated beginning at the bottom of the queue to determine whether the task deferral control block indicates a request for exclusive access. An indication of exclusive access for the current or last task deferral control block causes the pointers BEGPTR and BAKPTR to be reset. The chain of the queue is followed by the next control block pointer NCB in each task deferral control block pointing to the next most recently enqueued task until the top of the queue is indicated by NCB = 0 at which point 88 the current values of BEGPTR and BAKPTR point to the task deferral control blocks, as indicated in Figs. 8(A) and 8(B).

Referring again to Fig. 7, at the point 88 where BEGPTR and BAKPTR have been identified, a test is made as to whether the task deferral control block pointed to by BEGPTR indicates a request for exlusive access. If the least recently enqueued task is a request for exclusive access, as illustrated in Fig. 8(A), then NEWFLAG is set to the task identification for the task of the task deferral control block pointed to BEGPTR. However, if BEGPTR points to a task deferral control block that does not indicate a request for exclusive access, as illustrated in Fig. 8(B), then NEWFLAG is set to the negative of the length of the chain of task deferral control blocks requesting shared access pointed to by BEGPTR. In the illustrated example in Fig. 8(B), this value of NEWFLAG would be -3. These two alternative values of NEWFLAG would be the values for LOCKFLAG for exclusive and shared access respectively once the queue has been rearranged.

At the point 90 where NEWFLAG has been set to its proper value, a test is made as to whether a queue will exist after the intended rearrangement of the queue. If BAKPTR $\neq 0$, a queue exists. In this case 92, the next control block pointer NCB of the task deferral control block pointed to by BAKPTR is set to 0, indicating that this task will become the least recently enqueued task in the queue and LOCKFLAG is set to NEWFLAG in an MP-consistent operation. At this point 94, the queue has been rearranged and all that remains to be done is a resumption of the suspended tasks, disposition of the no longer used task deferral control blocks and a release of access by abnormally terminated tasks in block 96.

If, however, BAKPTR = 0 execution reaches point 98 indicating that no queue will be further necessary. In this case NEWTPTR is set to 0 to indicate the intended absence of a queue following atomic reference 100 with a compare double and swap. A successful test for OLD = LOCK means that no rearrangement of the queue has occurred since the last atomic reference. In this case LOCK is set to NEW and execution reaches point 94 for the abnormal termination clean-up, disposition of the task deferral control blocks and resumption of suspended tasks. If, however, the test was unsuccessful, OLD is replaced by LOCK and execution returns to point 84 to once again find the status of the queue.

The clean-up for abnormal terminations indicated in block 96 follows the flow diagram of Fig. 10. The purpose of the clean-up is to remove access for those tasks which have abnormally terminated (abended) while waiting in the queue for access to the resource. Every task which has been provisionally given access to the

resource is examined to determine whether it has abnormally terminated. If it has, its task deferral control block is added to an ABEND list resembling the queue with its next control block pointer pointing to the next most recently queued task deferral control block, if any in the ABEND list. If the task has not abnormally terminated, its execution is resumed, its task deferral control block is disposed of, and flags for shared access are set for each of those tasks which are to gain shared access. Finally, any abnormally terminated tasks have their access released and their task deferral control blocks disposed of.

It is to be appreciated, of course, that other embodiments of the invention exist than the one described here. Many of the described conventions can be arbitrarily changed. For instance, shared access could be denoted by a positive value of LOCKFLAG and exclusive access by a negative value. The order of LOCKFLAG and LOCKTPTR in the double-word LOCK is arbitrary. Indeed, a single word could be used for LOCK if individual bits or blocks of bits within the word can be set and tested.

Thus there have been described methods to request or release both shared and exclusive access to a resource using the atomic reference, compare double and swap. The hierarchy of task locking using these methods can be illustrated by the hierarchy shown in Fig. 1(C). The application task locking can use either a supervisor task exclusive or supervisor task share based on the compare double and swap forming the fundamental operation of the task lock. Thus the hierarchy involves only three levels of operation for either exclusive or

shared tasks, a simplification over prior art task locking.

Multi-task, multiprocessor applications can make use of this form of locking for the control of queues and resources between tasks within such applications. The location of the lockword for each resource so controlled must be known to each appropriate task and to its associated processing for abnormal termination. This reduces the hierarchy to only two levels of operation for such applications. Among the resources so controlled can be queues of lockwords. Such applications can thus provide their own symbolic lock processing and locking hierarchies at a substantial performance improvement over the use of corresponding services within the supervisor. Additionally, single-thread, multi-task applications, those consisting of tasks with their own form of dispatching, which currently have their own symbolic lock processing and locking hierarchies, can be converted to multitask, multi-processor operation. This results in a greater processing capability without the loss of performance or function gained by having their own symbolic lock processing and locking hierarchies.

It is seen that the supervisor task lock can be accomplished without spin-locks except as may be required when suspending or resuming task execution. Of course, supervisor spins are possible with compare double and swap. The advantages of the absence of spinning within the described methods are the elimination of the associated cost in performance, the ability to exploit this form of locking directly from multi-task, multiprocessor applications, and a reduction in the concern

for recovery from the CPU failure in which a spin-lock is held by the failing CPU.

Further advantages of the described methods are the very short path lengths required to obtain the lock when no conflict exists over the initial estimate of the status of the queue. This short pathlength is due in part to the initial guess for either request for access or release that the resource is not otherwise engaged. This short pathlength is also due to the economy of using access to the resource to provide that control of access required for manipulation of the first-in/first-out queue which is not provided by the atomic nature of compare double and swap. Another advantage of the described methods is that no free storage allocation for or preparation of task deferral control blocks or the like is required for access when the resource is immediately available.

Certain disadvantages do exist for the task locking methods described for this invention. If the owning task of a resource abnormally terminates, ABEND processing is required to know the location of each double word used as a resource identifier. The ABEND processing must release access of the resources on behalf of the task being terminated. The primary disadvantage for a shared resource access with this form of locking is the requirement that some form of flag associated with each task must be set to indicate shared ownership when held.

CLAIMS

1. A method for controlling access for a resource in a multi-task system with a first-in/first-out queue, comprising the steps of:

providing a first-in/first-out queue composed of entries for each task awaiting access to said resource, each entry containing an indicator for the next most recently enqueued task, and the entry for the least recently enqueued task containing an indicator of its being least recently enqueued;

providing storage space for a current lockword accessible to each task, said lockword containing a lock flag indicating the availability of said resource and a lock pointer pointing to the entry in the queue of the most recently enqueued task;

requesting a change in access of a task;

estimating a value for said lockword;

projecting a value for a first new lockword based on the estimated lockword and the requested change;

performing a first atomic reference with said task on said current lockword during which no other task can perform a similar atomic reference on said current lockword, said performance of said first atomic reference comprising comparing said estimated current lockword with said current lockword and, if said estimated current lockword matches said current lockword, replacing said

current lockword with the value of said first projected new lockword, thereby changing access to said resource.

2. A method for controlling access to a resource, as recited in Claim 1, wherein, for said requested change being a request for access, the first occurrence of said estimating step is a step estimating said current lockword to indicate that said resource is available.

3. A method for controlling access to a resource, as recited in Claim 1, wherein, for said requested change being a request for release of said access, the first occurrence of said estimating step is a step estimating said current lockword to point to no entry for an enqueued task.

4. A method for controlling access to a resource, as recited in Claim 1, further comprising:

projecting a value for a second new lockword based on said current lockword; and

performing a second atomic reference with said task on said current lockword if other tasks can change the entries to said queue gaining access to said resource as a result of said requested change;

wherein said steps of projecting a second new lockword and performing a second atomic reference are executed if said estimated current lockword does not match said current lockword in said first atomic reference.

5. A method for controlling access to a resource, as recited in Claim 1, wherein providing a queue comprises providing a storage space for a task deferral control block for each task awaiting access to said resource, each task deferral control block containing a pointer to the location of the next most recently enqueued task deferral control block and wherein said lock pointer points to the location of the most recently enqueued task deferral control block.

6. A method for controlling access to a resource, as recited in Claim 1, wherein said step of performing a first atomic reference further comprises replacing said estimated value of said current lockword with the actual value of said current lockword if said estimated value of current lockword does not match the actual value of said current lockword.

7. A method for controlling access to a resource, as recited in Claim 1, wherein said access to said resource provides that control of access required for manipulation of said first-in/first-out queue which is not provided by the atomic nature of said atomic references.

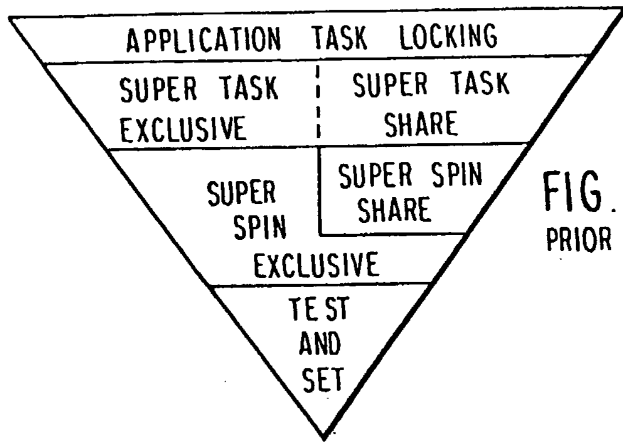


FIG.1A
PRIOR ART

FIG.1B
PRIOR ART

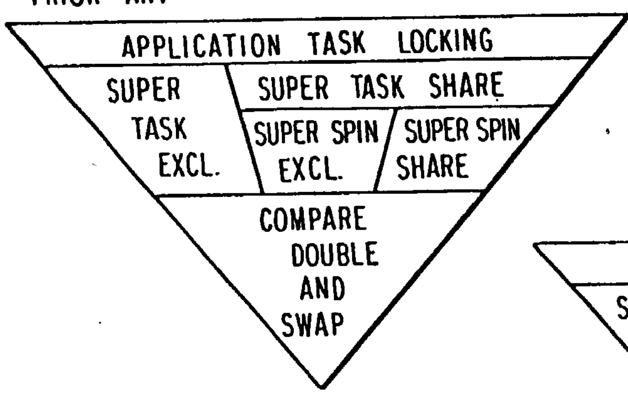


FIG.1C

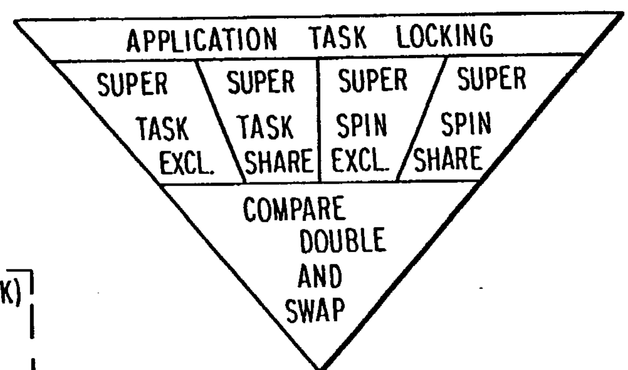
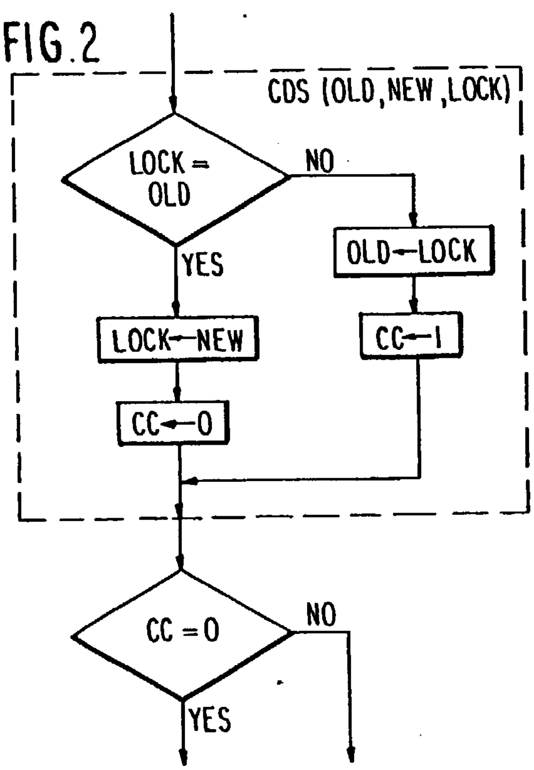


FIG.2



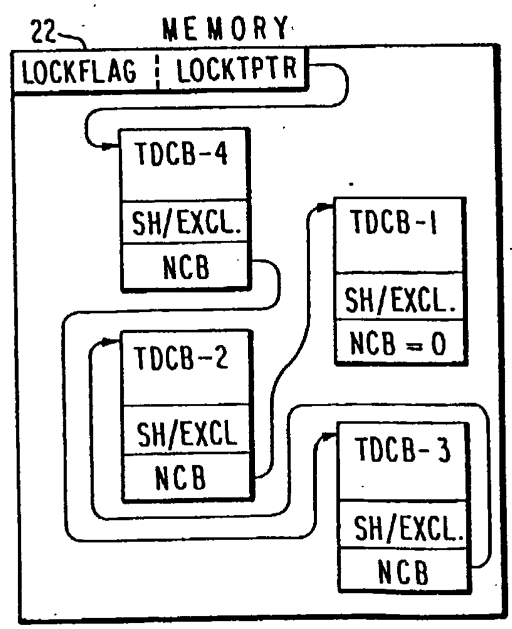


FIG.3

FIG.4

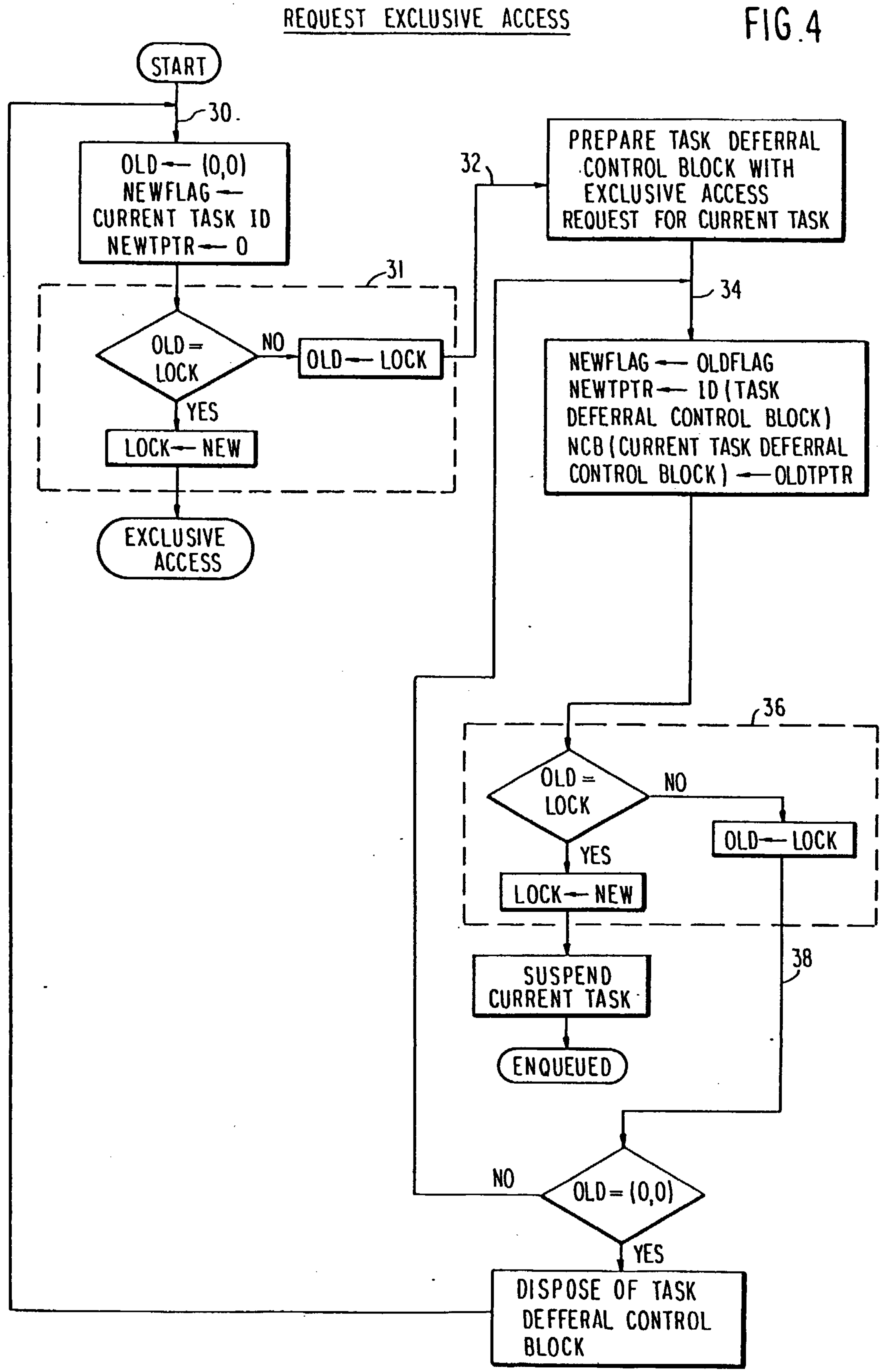

REQUEST EXCLUSIVE ACCESS
START
30
OLD ← (0,0)
NEWFLAG ← CURRENT TASK ID
NEWTPTR ← 0
31
OLD = LOCK
NO
OLD ← LOCK
YES
LOCK ← NEW
EXCLUSIVE ACCESS
32
PREPARE TASK DEFERRAL CONTROL BLOCK WITH EXCLUSIVE ACCESS REQUEST FOR CURRENT TASK
34
NEWFLAG ← OLDFLAG
NEWTPTR ← ID (TASK DEFERRAL CONTROL BLOCK)
NCB (CURRENT TASK DEFERRAL CONTROL BLOCK) ← OLDTPTR
36
OLD = LOCK
NO
OLD ← LOCK
YES
LOCK ← NEW
SUSPEND CURRENT TASK
ENQUEUED
38
NO
OLD = (0,0)
YES
DISPOSE OF TASK DEFFERAL CONTROL BLOCK

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FIG.5

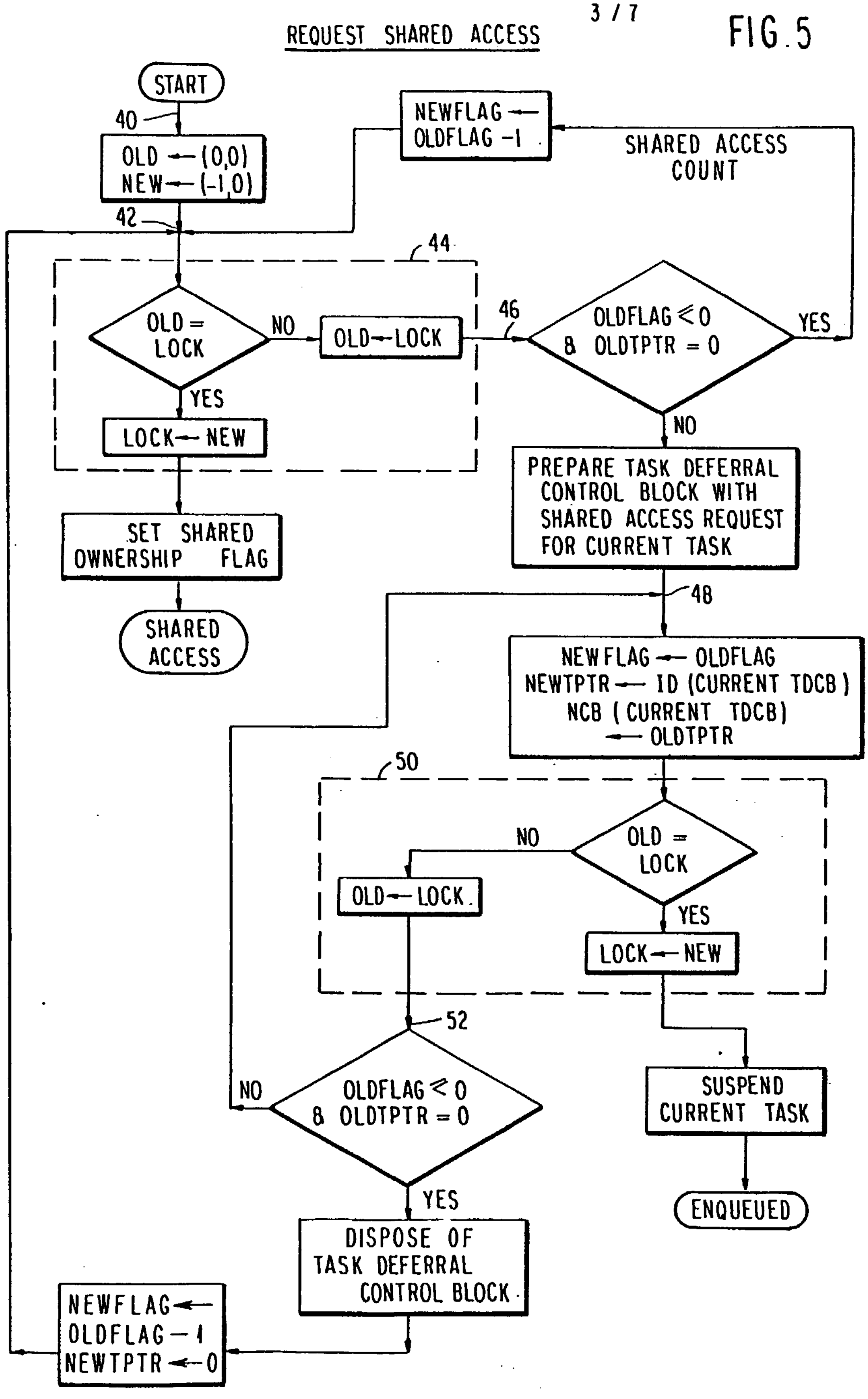
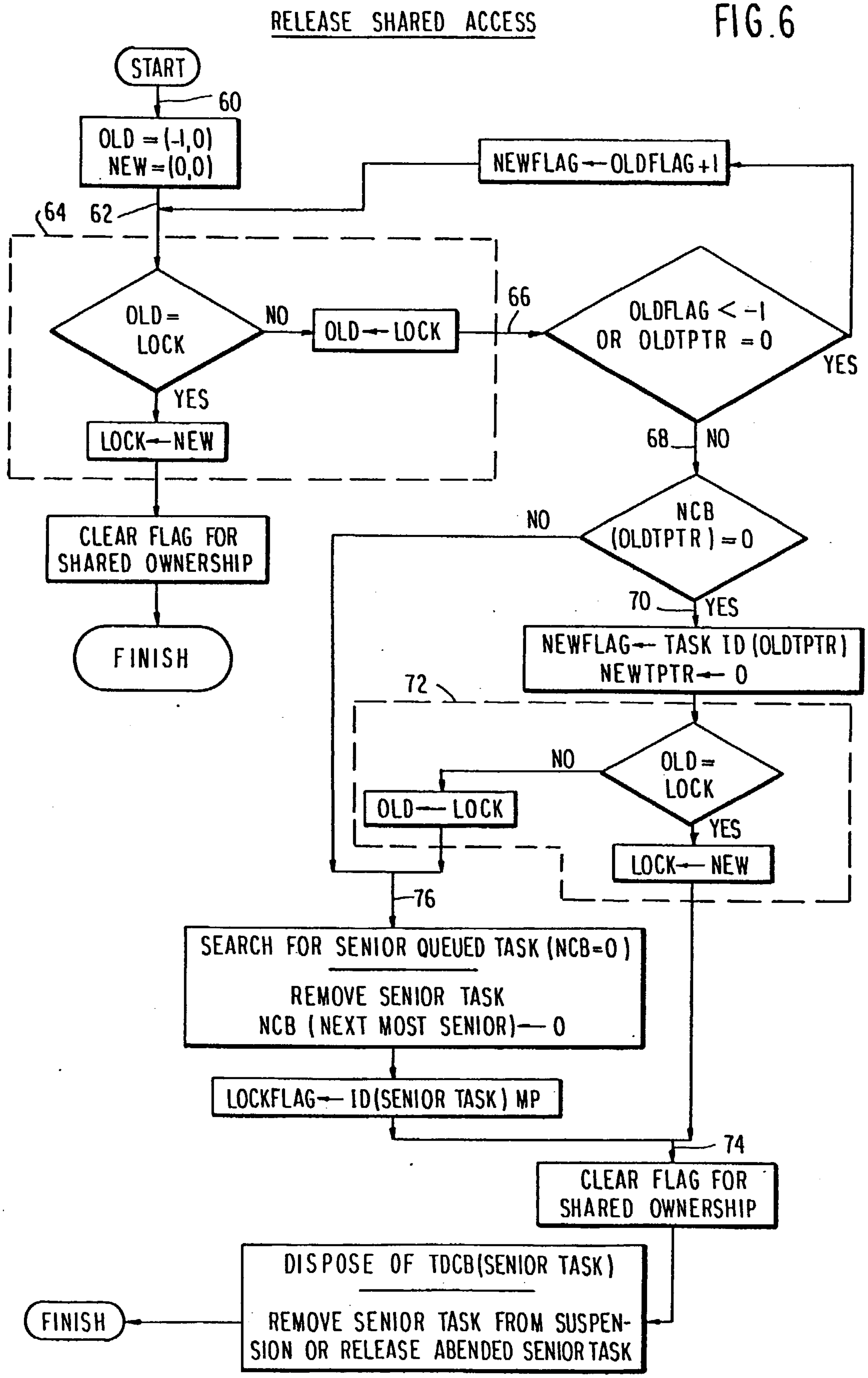
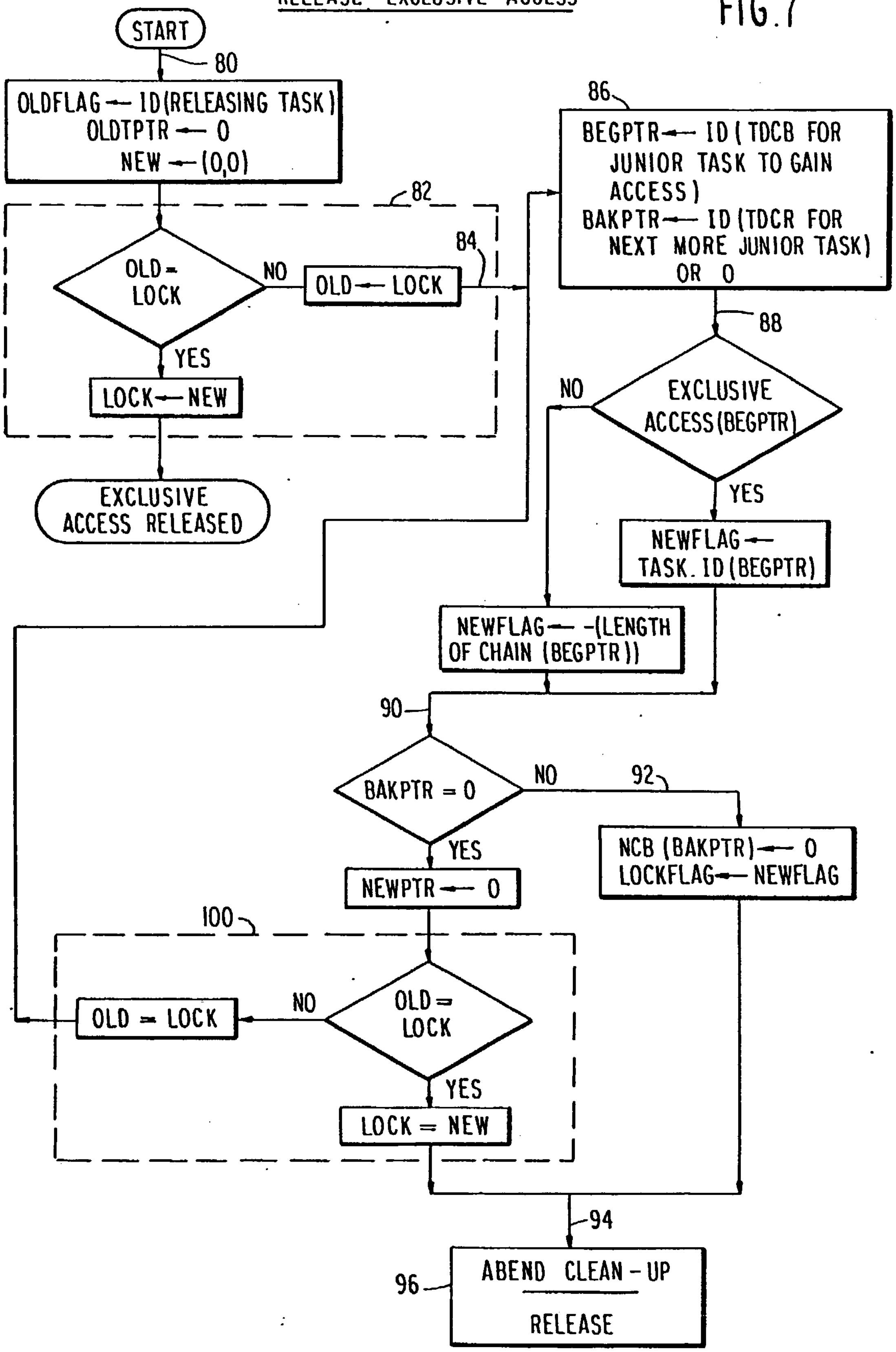


FIG.6


RELEASE SHARED ACCESS
START
60
OLD = (-1,0)
NEW = (0,0)
NEWFLAG ← OLDFLAG + 1
64
62
OLD = LOCK
NO
OLD ← LOCK
66
OLDFLAG < -1
OR OLDTPTR = 0
YES
YES
LOCK ← NEW
68
NO
CLEAR FLAG FOR
SHARED OWNERSHIP
NO
NCB
(OLDTPTR) = 0
FINISH
70
YES
NEWFLAG ← TASK ID (OLDTPTR)
NEWTPTR ← 0
72
NO
OLD = LOCK
OLD ← LOCK
YES
LOCK ← NEW
76
SEARCH FOR SENIOR QUEUED TASK (NCB=0)
REMOVE SENIOR TASK
NCB (NEXT MOST SENIOR) ← 0
LOCKFLAG ← ID(SENIOR TASK) MP
74
CLEAR FLAG FOR
SHARED OWNERSHIP
DISPOSE OF TDCB(SENIOR TASK)
FINISH
REMOVE SENIOR TASK FROM SUSPEN-
SION OR RELEASE ABENDED SENIOR TASK

RELEASE EXCLUSIVE ACCESS

FIG.7



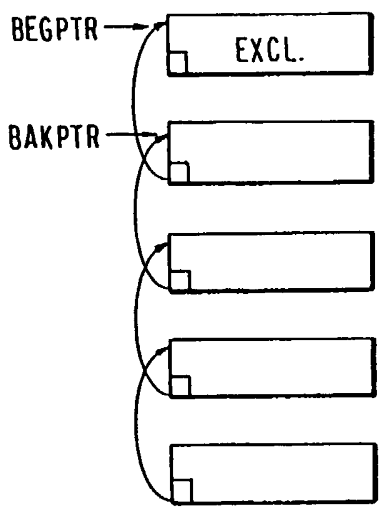


FIG. 8A

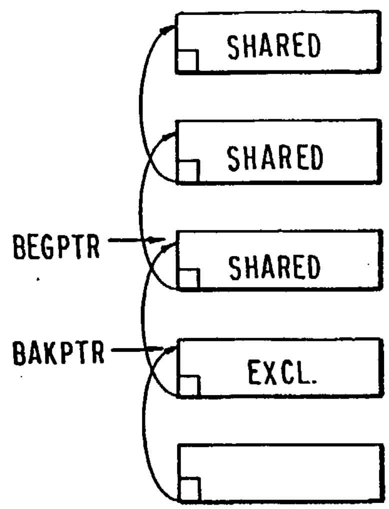


FIG. 8B

FIG. 9

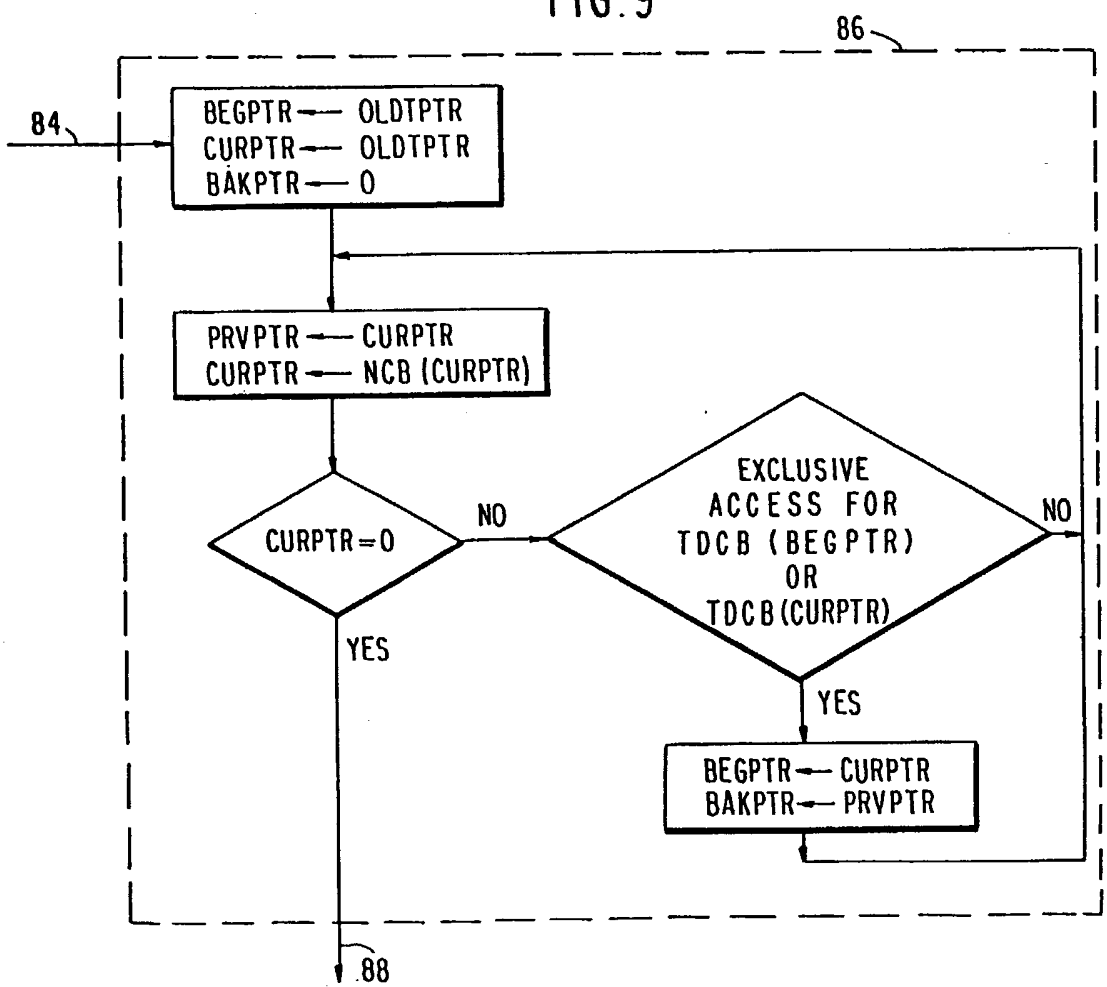
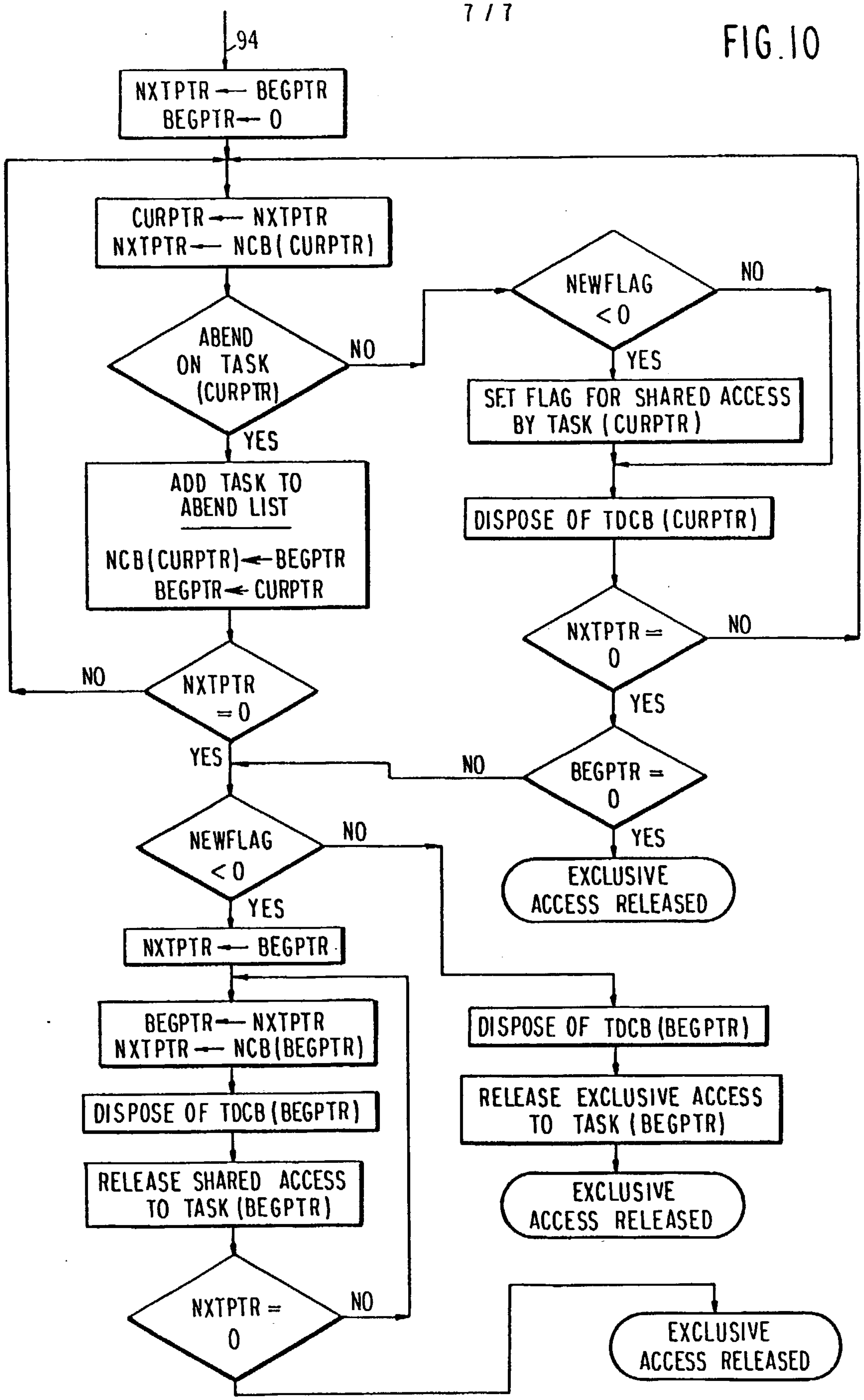


FIG.10


94
NXTPTR ← BEGPTR
BEGPTR ← 0
CURPTR ← NXTPTR
NXTPTR ← NCB(CURPTR)
ABEND ON TASK (CURPTR)
NO
YES
ADD TASK TO ABEND LIST
NCB(CURPTR) ← BEGPTR
BEGPTR ← CURPTR
NXTPTR = 0
NO
YES
NEWFLAG < 0
NO
YES
SET FLAG FOR SHARED ACCESS BY TASK (CURPTR)
DISPOSE OF TDCB (CURPTR)
NXTPTR = 0
NO
YES
BEGPTR = 0
NO
YES
EXCLUSIVE ACCESS RELEASED
NEWFLAG < 0
NO
YES
NXTPTR ← BEGPTR
BEGPTR ← NXTPTR
NXTPTR ← NCB(BEGPTR)
DISPOSE OF TDCB (BEGPTR)
RELEASE SHARED ACCESS TO TASK (BEGPTR)
NXTPTR = 0
NO
DISPOSE OF TDCB (BEGPTR)
RELEASE EXCLUSIVE ACCESS TO TASK (BEGPTR)
EXCLUSIVE ACCESS RELEASED
EXCLUSIVE ACCESS RELEASED